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International Emissions Trading and Induced Carbon-Saving Technical Change: Effects of Restricting the Trade in Carbon Rights

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Abstract

This paper examines the implications of restricting the tradability of carbon rights in the presence of induced technical change. Unlike earlier approaches aiming at exploring the tradability-technology linkage we focus on climate-relevant 'carbon-saving' technical change. This is achieved by incorporating endogenous investment in carbon productivity into the RICE-99 integrated assessment model of Nordhaus and Boyer (2000). Simulation analysis of various emission reduction scenarios with several restrictions on emissions trading reveals a pronounced dichotomy of effects across regions: Restrictions to trading raise the investments in carbon productivity in permit demanding regions while reducing them in permit supplying regions. In terms of per capita consumption, permit demanding regions lose and permit supplying regions gain from restrictions. In scenarios that involve 'hot air', restrictions to trade lower overall emissions which results in reduced climate damage for most regions. Reduced damage, in turn, reduces the incentive to invest in carbon productivity.

Keywords: carbon-saving technological progress, emissions trading, flexibility mechanism, induced technological change, integrated assessment model

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1 Introduction

Climate change due to anthropogenic carbon emissions has been a source of growing concern within the last decades. In environmental-economic research a great deal of effort has been devoted to estimating the costs and benefits of carbon abatement policies (IPCC 2001). In addition, the search for strategies to reach carbon abatement targets in a cost-effective manner has been an important research topic and a hot issue in international climate negotiations.

With respect to cost-effectiveness, an important feature of carbon abatement is that it represents a purely global common. That is, it does not matter where abatement takes place. In such circumstances, standard economic reasoning suggests that overall costs are minimized when abatement is allocated among parties in such a way as to equalize marginal abatement costs. Such an allocation can be sustained by market-based mechanisms. Hence, the conclusion is that market-based instruments indeed lower the total cost of achieving a given overall abatement target, by enhancing an equalization of marginal abatement costs across parties.

This line of reasoning has played a key role in international climate diplomacy. A major outcome of the climate negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) is the Kyoto Protocol (KP). For the first time in history, a group of signatory countries, the so-called Annex B countries of the KP, obligated themselves to quantitative emission limits[1]. An important ingredient to the KP is the introduction of so-called flexibility mechanisms. The most far-reaching of these mechanisms is emissions trading (ET). Under ET each country may choose either to reduce emissions to comply with its emission limit or to buy additional permits. Likewise, each country can reduce more than necessary and sell permits. The fundamental constraint is that the overall emission limit of all trading parties be satisfied. This enables the (industrialized) countries to reduce carbon emissions where and how it is cheapest[2].

In spite of their presumed benefits, the flexible Kyoto mechanisms are much debated. One argument is that they prevent countries from investing in technological progress. Placing

[1] Annex B countries comprise mainly western industrialized countries and the countries in transition in Eastern and Central Europe

restrictions on flexibility may in this view imply long-term benefits due to induced technological change (see eg. Hourcade and LePesant 2000, Grubb, Brack and Vrolijk 1999, Oberthür and Ott 1999). In the political arena, this and related reasoning has motivated demands that ceilings should be imposed on the degree to which emissions are tradable.

This paper examines the implications of ceilings on emissions trading in climate policy when there is induced carbon-saving technical change. To that purpose we extend the well-known RICE-99 integrated assessment model of Nordhaus and Boyer (2000) by endogenizing 'decarbonization' hitherto included in RICE-99 in an exogenous fashion. More specifically, we introduce into the model a stock of knowledge, being the result of cumulative R&D spending, which raises the productivity of carbon energy in terms of the energy services that can be derived from it. The model extended in this way is used to simulate several variants of carbon abatement scenarios considered in the previous literature. These abatement scenarios are combined with different assumptions on the admissible degree of emissions trading.

There have been earlier approaches at endogenizing technological progress in economic models of climate change[3], but only few attempts to analyze the linkage between the flexibility mechanisms and induced technological change. To our knowledge only Buonanno et al. (2001) have so far analyzed restrictions to emissions trading in the presence of induced technological progress, using an earlier vintage of the RICE model as the basis for modeling technological change. In that version of RICE (see Nordhaus and Yang 1996), energy is not portrayed explicitly, neither as a production input nor as a source of carbon emissions. Rather, there is a 'reduced form' representation of production and emissions, the latter being proportional to output. In the Buonanno et al. (2001) extension an endogenous knowledge stock is introduced which serves the twin purpose of raising total factor productivity, thus enhancing output, and reducing the emission-output ratio. The effect of this type of technological progress on emissions is ambiguous a priori.

Using RICE-99 as the basis for our modeling work allows us to focus on that category of technological progress - decarbonization - which is most likely to respond to the rationing of

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[2] Other mechanisms are Joint Implementation and the Clean Development Mechanism. Joint implementation allows industrialized countries to reduce emissions via investment in other industrialized countries. The clean development mechanism is similar but allows investors to claim credit for reductions in developing countries.
[3] See Weyant and Olavson (1999) and Löschel (2002) for overviews. More recent examples are Buonanno et al. (2003) and Popp (2003).

carbon emissions.[4] Using this approach we find a pronounced dichotomy of effects across regions: Restrictions to trading raise the investments in carbon productivity in permit demanding regions while reducing them in permit supplying regions. In terms of per capita consumption, permit demanding regions lose and permit supplying regions gain from restrictions. In scenarios that involve 'hot air', trade restrictions lower overall emissions which results in reduced climate damage for most regions. Reduced damage, in turn, reduces the incentive to invest in carbon productivity.

The paper is organized as follows. In Section 2, we highlight the role of induced technological change in carbon abatement policy and its interplay with emissions trading. Section 3 is dedicated to our modeling approach. In section 4, we introduce the scenarios examined and present and discuss our simulation results. Section 5 concludes.

2 Emissions Trading and Induced Technological Change

2.1. Conceptual Background

Standard economic reasoning suggests that emissions trading minimizes the cost of carbon abatement by equalizing differentials in marginal abatement cost. This line of thought has largely attracted policy makers in international climate negotiations especially from industrialized countries and has entered the Kyoto-Protocol as the well-known flexibility mechanisms. Nevertheless, the attractiveness of these mechanisms has been called into question for several reasons. One line of reasoning maintains that the possibility of buying emission permits from abroad instead of domestic abatement reduces the incentives for environmental friendly innovation and the development of low carbon technologies (see eg. Hourcade and LePesant 2000, Grubb, Brack and Vrolijk 1999, Oberthür and Ott 1999). The converse of this view implies that placing restrictions on emissions trading is beneficial in the long term since it stimulates the creation of technologies which provide the opportunity to lessen the (negative) environmental impacts of economic growth or, likewise, make higher economic activity levels sustainable in the presence of binding environmental constraints.

The responsiveness of technological progress to economic incentives - on which these arguments rely - has long been acknowledged in economic research and come to be known as

[4] Another difference between our work and that of Buonanno et al. (2000) is that we consider a finer regional

'induced innovation hypothesis'. The basic idea is that technological progress is the result of R&D activities that are costly and ultimately emerge as " …an endogenous equilibrium response to Schumpeterian profit incentives" as Jaffe et al. (2000, p. 20) put it.[5] One robust feature of these models is the presence of scale effects. This means that the incentives to engage in R&D as well as the resulting level of technological progress are an increasing function of the size of the market in which the new technology can be applied.

Within the broad field of induced innovation, it is convenient to distinguish two lines of research. One focuses on the determinants of total factor productivity which were kept unexplained in neoclassical growth theory. Endogenous growth theory (Aghion and Howitt 1998) tackled this issue by endogenizing technological change. It is characteristic of this literature that those production inputs which ultimately lead to environmental emissions - especially energy - are usually not considered. Consequently, the environmental consequences of this kind of technological progress (total factor productivity improvement) remain unclear.

While this literature is concerned with 'undirected' technological change, what seems more relevant to the subject of this paper is technological change specifically directed towards environmentally relevant inputs. This issue is akin to the theory of 'induced bias in innovation', a branch of research initiated two decades earlier than endogenous growth theory which relates to the question how the *specific* productivity of a particular factor of production evolves in response to economic conditions. The basic prediction from this literature (see Stoneman 1983) is that - unless factors are highly substitutable - an increase in the relative price of one factor triggers technological change such that the productivity of this factor increases, a phenomenon referred to as induced factor-saving technological change.[6]

To the extent that restrictions to permit trading make carbon use more expensive, it is consistent with the results from this literature that trade restrictions may stimulate carbon saving technological change. This reasoning will apply to potential buyers of carbon permits. On the other hand, however, suppliers of permits will also engage in carbon-saving R&D, and they will do the more so the larger is the permit market. Indeed, carbon-saving technological

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disaggregation (13 world regions instead of 6) and a greater variety of abatement scenarios.

[5] Investment in R&D is one among other possible ways (such as R&D spillovers or technological learning) to endogenize innovation (see, e.g., Löschel 2002).

[6] The distinction between total factor productivity and factor-specific productivity provides a useful framework for our approach at endogenizing technological change (see section 3.2). It does not imply that factor-specific technological change is necessarily irrelevant for growth.

change makes more carbon permits abundant in the supplier countries, so they can be sold in the market. In this sense, the possibility to sell additional permits acts as an incentive to undertake carbon-saving R&D, and these incentives increase in the size of the market (scale effect). Conversely, restricting the tradability of permits reduces R&D incentives in these countries.

It is thus not to be expected that trade restrictions *universally* trigger carbon-saving R&D. Moreover, even if induced R&D rises, given restricted possibilities of buying permits, it is not clear whether a country taking resort to increased R&D might not be better off on balance if trade restrictions were removed and 'forced' R&D expenditures were saved. These are rather complicated questions that cannot be resolved a priory. Rather, they need careful empirical modeling of the issue.

2.2. The Policy Context

In addition to the general logic just outlined, a further aspect is introduced by the particularities of the abatement targets as laid down in the KP. The Kyoto commitments are calculated with respect to the emission levels of 1990. This was just before the collapse of emissions in the former Soviet Union in the aftermath of transition. As a result of this collapse, the former Soviet Union is endowed with a huge amount of abundant emission rights.

The implications of this circumstance vary sharply with the admissible extent of emissions trading. Under full ET, abundant permits would in their entirety represent emission reduction credits accessible to all other countries. As a result, no abatement action would be required at all for a considerable period of time in order to satisfy the overall Kyoto commitment (Grubb et al. 2001). The western industrialized countries – which are the main polluters – could simply buy cheap emission reduction credits, a phenomenon known as trade in ‘hot air'.

With respect to induced technological change, the possibility of 'hot air' trade would likely remove significant portions of the incentive to engage in carbon-saving R&D beyond business-as usual levels. This effect has further intensified since the US’ recession from the KP because only the US demand for permits could have bid up the permit price sufficiently to act as an incentive for R&D.

In a more long-term perspective, neither the Kyoto targets nor the withdrawal of the US may be the 'last word'. Scientific evidence demands for much higher emission reductions than the Kyoto targets. Consequently, the KP should be regarded only as a first step in a process of sequential (yet unknown) commitments towards more ambitious emission reduction in the future. With more ambitious abatement targets the incentives for carbon-saving R&D will rise even under full ET.

To explore these issues we will examine not only a scenario involving the Kyoto abatement targets (*Kyoto Forever*) but also one in which the Kyoto targets become stricter over time (*Kyoto Dynamic*). In addition, a scenario will be considered in which abatement targets are not exogenously specified but derived from given ceilings on the atmospheric carbon concentration (*Concentration target*).[7]

3 The Model

3.1. Basic Framework and Previous Modeling of Endogenous Technical Change

We use the well-known RICE model of integrated assessment as our basic modeling framework and extend it by endogenizing technological change. Unlike Buonanno et al. (2001) we employ an updated version, referred to as RICE-99 (Nordhaus and Boyer 2000), which incorporates an explicit treatment of the linkage between carbon energy, the energy services that can be derived from it, and the resulting carbon emissions.

The RICE model is a multi-region single sector optimal growth model, coupled with a simple representation of the carbon cycle.[8] Within each region, the optimal paths of fixed investment and emission abatement are chosen that maximize the present value of consumption-based utility. Population (taken to be equal to full employment) and technology levels grow over time in an exogenous fashion. Atmospheric carbon levels are fed by carbon emissions and feed back on production possibilities, thus driving a wedge between output gross and net of climate change effects.

[7] The choice of these scenarios is partly inspired by the scenarios examined in the Energy Modeling Forum (see Weyant and Hill 1999, pp. xiii-xiv).
[8] See Appendix 1 for a general description.

Notwithstanding these general characteristics, several vintages of the RICE model exist which differ in terms of a number of features. The differences most relevant for the present paper concern the specification of the production process, the emission function, and the number of world regions.[9] We first provide a brief discussion of RICE-96 (Nordhaus and Yang 1996) and how it was extended by Buonanno et al. (2001) to account for endogenous technological change. The next section will be devoted to our extension of RICE-99.

RICE-96 features six regions (US, Japan, Europe, China, Former Soviet Union, Rest of the World). Output is produced according to a constant returns Cobb-Douglas technology in capital and labor with exogenous total factor productivity and used for investment and consumption. Carbon emissions are proportional to output, where the emission-output ratio is variable, due to abatement activities. The latter imply a deduction from output.

These relations form the basis for the technical change extension performed by Buonanno et al. (2001). Their approach is to introduce a stock of knowledge K_R which represents the level of technology and which evolves endogenously as a result of R&D expenditures. In particular, output Q and emission E are specified in this extended version of RICE-96 as follows:

$$Q_{j,t} = \Omega_{j,t}(1 - b_{1t}\mu_{j,t}{}^{b2})A_{j,t}K_{R_{j,t}}^{\beta_j}K_{j,t}{}^{\gamma}L_{j,t}^{1-\gamma} \tag{1}$$

$$E_{j,t} = (1 - \mu_{j,t})(\sigma_{j,t} + \chi_{j,t}e^{-\alpha_n K_{R,j,t}})A_{j,t}K_{R_{j,t}}^{\beta_j}K_{j,t}{}^{\gamma}L_{j,t}^{1-\gamma} \tag{2}$$

In this formulation j refers to the model regions and t to time periods (of 10 years length). In equation (1) Q is output net of climate change effects and emission abatement. K and L denote capital and labor, respectively, and A is total factor productivity. Net output takes into account the (mostly negative) feedback of the climate system by the climate damage coefficient (Ω) and total abatement cost that depend on the abatement cost parameter (b) and the emission control rate (μ) that is the policy variable. According to equation (2) emissions depend on gross output, the emissions control rate, and the carbon intensity of production represented by the term $\sigma+\chi\cdot\exp(-\alpha K_R)$.

[9] Other differences relate to the treatment of energy supply and the specification of the climate module (see Nordhaus and Boyer 2000).

This specification is an extension of the formulation of Nordhaus and Yang (1996) in the sense that the latter can be recovered from the former by setting the production elasticity of knowledge β and the scaling coefficient χ equal to zero. With β and χ strictly positive, a growing level of knowledge K_R serves two purposes: it increases total factor productivity and decreases carbon intensity of output. This approach is justified by Buonanno et al. (2001) by pointing to the difficulty of specifying and calibrating a model with different types of R&D.

3.2. Carbon-Saving Technological Change

A limitation of the RICE-96 model and its extension is the reduced-form representation of the production structure and emission function. RICE-99 provides a respecification of these relationships, designed to explicitly capture 'carbon energy' in its twin role as a production input and source of emissions. This reformulation is useful since it permits to incorporate the concept of carbon-saving technological change. In RICE-99 as described in Nordhaus and Boyer (2000), carbon-saving technological change is exogenous. Consistent with the theory of induced bias in innovation discussed in section 2.1, it is carbon-saving technological change that is most likely to respond to limitations to carbon use. It is this response that we aim to model.

The production structure in RICE-99 can be written as follows:

$$Q_{j,t} = \Omega_{j,t}\left[A_{j,t} K_{j,t}^{\gamma} L_{j,t}^{1-\beta_j-\gamma} ES_{j,t}^{\beta_j} - c_{j,t}^{E} ES_{j,t} \right] \tag{3}$$

$$ES_{j,t} = \varsigma_{j,t} E_{j,t} \tag{4}$$

$$\varsigma_{j,0} = 1 \tag{5}$$

In this formulation a new input called energy services (ES) enters the production function (3). Since energy services are a produced input, the term $c^E \cdot ES$ in equation (3) subtracts from gross output the costs of producing this input. As specified in equation (4), energy services are derived from fossil fuel consumption (E). Fossil fuel consumption is equal to the carbon content of fossil fuels, that is fossil energy is lumped into a single aggregate where the different fuels are aggregated using carbon weights. Fossil energy use can be identified with (energy-related) carbon emissions.[10]

[10] For convenience, both are measured in carbon units.

Technological change takes two forms: economy-wide technological change (change of total factor productivity, A) and carbon-saving technological change. Economy-wide technological change is Hicks-neutral, while carbon-saving technological change is modeled as reducing the ratio of CO_2 emissions to energy services or, equivalently, raising energy efficiency ς = ES/E (whose base-year value is normalized to one, see equation (5)). Because of carbon saving technological change, society is able to squeeze more energy services per unit of carbon energy.

In RICE-99 both A and ς are projected exogenously into the future. Since the share of carbon energy in gross output is small restrictions to carbon energy use will mainly affect ς. Therefore, we retain the exogeneity assumption with respect to total factor productivity. Carbon-saving technological change, however, is endogenized to reflect that economic agents will invest in energy-related knowledge to raise fossil energy efficiency when carbon use is restricted.

The idea of induced energy efficiency improvement (or likewise carbon-saving technological change) is captured by introducing a new variable, energy-related knowledge (K_E). Its influence on energy efficiency is specified in the probably most parsimonious way:

$$\varsigma_{j,t} = \left(\frac{K_{E,j,t}}{K_{E,j,0}} \right)^{\varepsilon_{j,t}} \tag{6}$$

As can be seen from equation (6), the index of energy efficiency ς is an iso-elastic function of the stock of knowledge relative to the benchmark period. This formulation ensures that the energy efficiency index equals unity in the base-year and matches the initial value of ς from the exogenous specification.[11]

The energy-related knowledge stock evolves in the following way:

$$K_{E,j,t+1} = (1-\delta)K_{E,j,t} + I_{E,j,t} \tag{7}$$

[11] It may be noted that upon inserting (6) in (4) and the result in (3) one obtains a production function for gross output with inputs capital, labor, energy-related knowledge, and carbon energy which exhibits increasing returns to scale.

Energy-related knowledge thus accumulates according to the perpetual inventory model. Knowledge can be accumulated through investments (I_E) and the stock is subject to depreciation according to the depreciation rate δ (=5%).

Now the economic agents have an additional strategic variable to lower emissions: instead of substituting physical capital for energy or lowering production they can lower emissions by investing in energy knowledge via R&D. However, scarce resources have to be devoted to this purpose that compete with investments in physical capital (I) and consumption (C). The macroeconomic expenditure constraint thus reads:[12]

$$Q_{j,t} = C_{j,t} + I_{j,t} + I_{E,j,t} \tag{8}$$

Overall, in RICE-99 extended to account for induced energy efficiency improvements, output (net of energy costs and climate change effects) is allocated to consumption and two types of investment. This is achieved in an inter-temporal forward-looking manner, the objective function being the present value of discounted utility.

3.3 Emissions Trading and Technical Change

Emissions Trading (ET) is introduced via the imposition of emission constraints or targets on regions and grouping them in a so-called trading bloc.[13] Emissions trading requires to modify the regional expenditure constraints to account for purchases or sales of emission permits:

$$Q_{j,t} = C_{j,t} + I_{j,t} + I_{Ke,j,t} + p_t PD_{j,t} \tag{9}$$

$$PD_{j,t} = E_{j,t} - \bar{E}_{,j,t} \tag{10}$$

where p denotes the permit price. PD denotes permit demand and is defined as actual emissions E less the assigned amounts $\overline{E}$ that are allocated to the respective regions in the various abatement scenarios. Clearly, PD and the resulting flow of funds p·PD can be positive or negative, depending on whether a region is a permit buyer or a permit seller. The sum of

[12] Note that the RICE model does not feature international trade, except for trade in carbon permits (see below).
[13] Two trading blocs will be considered in our simulations: The Annex B countries, and the entire world.

permit demands within a trading bloc is required to be non-positive, i.e. the total emissions within a trading bloc must not exceed the emissions which the bloc is entitled to. The permit price is the dual or shadow value associated with this constraint.

Restrictions on ET are modeled by placing a trading quota on a region's abatement requirement. The quota is exogenously set between zero and unity and determines the maximum amount of ET allowed with respect to domestic action.

$$PD_{j,t} \le Quota\left(E_{Bau,j,t} - \bar{E}_{,j,t} \right) \tag{11}$$

In principle, it may be the case that a quota is not binding, i.e. the endogenously determined amount of trade falls short of the maximum trade volume allowed.

3.4 Empirical Implementation

The RICE-99 model of integrated assessment features the 13 world regions listed in Table 1. The model is solved in time steps of 10 years, the base-year being 1994. The time horizon is 200 years.

Table 1: World Regions in RICE-99

Annex B	**Non-Annex B**
EE (Eastern Europe) EUR (OECD Europe) Japan OHI (Other High Income Countries) Russia USA	Africa China HIO (High Income OPEC) India LI (Low Income Countries) LMI (Lower & Middle Income Countries) MI (Middle Income Countries)

The model regions differ not only with respect to their economic characteristics but also with respect to their vulnerability to climate change. Even though most regions are in general negatively affected by climate change, some regions may benefit from small degrees of global warming. Both the economic and climate-related characteristics of the regions are reflected in the calibration of the model. Moreover, the dynamic evolution of the model regions under business-as-usual (BAU) assumptions (that is, without limits to carbon emissions) is driven by projections concerning population and rates of technological change. With respect to the data and calibration of the basic model, the reader is referred to Nordhaus and Boyer (2000).

In implementing our model extension, the basic data and projections of RICE-99 are retained as far as possible. In addition, data for investment in energy efficiency from IEA (1997) are used to construct benchmark data for I_E (as appearing in equation (8)) and K_E (as appearing in equation (6)).[14] Given the augmented data set, it is possible to calibrate the extended model.

In our calibration we wish to benefit from the expertise devoted by Nordhaus and Boyer (2000) to the design of their BAU scenario. That is we want to reproduce the BAU trajectories of emissions as well as GDP and its uses (consumption and investment in physical capital). Our approach is to calibrate the elasticity of energy efficiency with respect to energy-related knowledge, ε, in such a way that the exogenous projection of carbon-saving technological change (ς) is met. In general, the parameters resulting from this procedure lie between zero and unity, meaning that there is a concave relationship between the level of K_E and energy productivity.[15] In addition, total factor productivity (A) is adjusted to accommodate the modified expenditure constraint (equation (8)).

It should be noted that our calibration of endogenous carbon-augmenting technical change leaves net output (GDP) unaffected. In this regard, we follow Nordhaus and Boyer (2000), who are careful in avoiding output-enhancing effects of increased carbon productivity.

4 Scenarios and Results

4.1 Description of Scenarios

We consider three abatement scenarios which are variants of scenarios previously considered in the literature (see Weyant and Hill 1999, pp. xiii-xiv): (a) Kyoto Forever (KyEv), (b) Kyoto Dynamic (KyDyn) and (c) a scenario that restricts atmospheric concentration of carbon to 500ppm. All cases are run with four different degrees (100%, 75%, 50% and 25%) of emissions trading (ET). Therefore, apart from the BAU-scenario, we arrive at 12 scenarios (see Table 2).

[14] See Appendix 2 on the procedure and results.

All cases have in common that they start with the Annex B emission targets and ET within the Annex B-bloc without the US in 2014. That is, they start with the 'Bonn-Marrakech-Accord'[16] (BMA). The first commitment period of the KP is 2008 – 2012. Due to the so-called commitment reserve, parties are only allowed to sell a small fraction of their allowed emissions until the end of the commitment period (Woerdman 2002, p. 89). Therefore, actual ET is only expected to begin thereafter when the required reporting and monitoring procedure is completed. In line with this time frame, compliance and ET of Annex B (without the US) in all scenarios are assumed to start in 2014. A basic assumption of all scenarios is that the US will re-join the climate change community in the second commitment period. That is, the US will comply with their respective targets and join the trading bloc in 2024.

Table 2: Scenarios

Bau	Business-as-usual
KyEv100	Kyoto forever, 100% Annex B-ET
KyEv75	Kyoto forever, 75% Annex B -ET
KyEv50	Kyoto forever, 50% Annex B -ET
KyEv25	Kyoto forever, 25% Annex B -ET
KyDyn100	Kyoto dynamic, 5% reduct. Per decade, 100% Annex B -ET
KyDyn75	Kyoto dynamic, 5% reduct. Per decade, 75% Annex B -ET
KyDyn50	Kyoto dynamic, 5% reduct. Per decade, 50% Annex B -ET
KyDyn25	Kyoto dynamic, 5% reduct. Per decade, 25% Annex B -ET
500ppm100	Concentration target: 500 ppm, equal burden sharing, 100% global ET
500ppm75	Concentration target: 500 ppm, equal burden sharing, 75% global ET
500ppm50	Concentration target: 500 ppm, equal burden sharing, 50% global ET
500ppm25	Concentration target: 500 ppm, equal burden sharing, 25% global ET

In the Kyoto forever case (KyEv%), the Annex B regions (Japan, OECD Europe, OHI, Russia and Eastern Europe) have emission permits according to their Kyoto targets and start Annex B ET in 2014, i.e. in the first commitment period. These targets remain valid for the whole time horizon of the model. Similarly, in 2024 (the second commitment period) the US complies with their Kyoto target and joins ET as well for the rest of the time horizon.

In the Kyoto dynamic case (KyDyn%), the permits of the Annex B regions (without the US) are reduced by 5% per decade with respect to their Kyoto targets, starting in the second commitment period. That is, in 2024, their target is 95% of the Kyoto emissions; in 2034, it is

[15] This is in line with previous literature, see Goulder and Mathai (2000).
[16] The emission targets are calculated without any 'loopholes'. That is, without any measures in land use, land use change and forestry (LULUCF) that might be counted as carbon credits.

90% a. s. o. The US complies with the same dynamic commitment, lagging one decade behind. That is, in 2024, when the Annex B already reduce their targeted emissions by 5% with respect to the Kyoto target, the US are committed to their Kyoto target and start the same reductions thereafter.

In the 500 ppm case (500ppm%), all remaining world regions (including the US) join the Annex B trading bloc in the second commitment period, thus creating worldwide ET. This case is characterized by equal burden sharing for all regions. That is, all world regions have to reduce their emissions by the same percentage from BAU emissions necessary to maintain the concentration target. The necessary percentage emission reduction is obtained from an earlier model run with an upper bound on the atmospheric concentration in the climate module. If the resulting emissions targets are higher than the Kyoto targets, the Annex B regions stick to their Kyoto commitment until the concentration target requires further reductions. The exception, again, is the US who is assumed not to be committed to the Kyoto targets but only to the emission limit derived from the concentration target subject to equal burden sharing.

4.2 Basic Simulation Results

In order to understand how restrictions to ET affect induced energy efficiency improvements it is useful to present some basic qualitative effects of imposing the various carbon abatement requirements under full emissions trading. These effects are compiled in Table 3.

Table 3: Basic Effects of Carbon Abatement under Full Emissions Trading

	(A) Emission constraint <u>not</u> binding	**(B) ET as % of buyers' abatement duty**	**(C) Buyers of permits**	**(D) Sellers of permits**	**(F) Abatement detrimental**
KyEv	Russia EE Japan (from 2034 on) EUR (from 2034 on)	84% (2034) - 100% (from 2074 on)	USA OHI EUR (2014) Japan (2014)	Russia EE; EUR (from 2024 on) Japan (from 2024 on)	Russia (2044-74) EE (2044-54) OHI(2034-64)
KyDyn	Russia EE	43% (2094) - 92% (2014)	USA OHI EUR (2014) Japan (2014)	Russia EE; EUR (from 2024 on) Japan (from 2024)	Russia (2044-74) EE 2044-54 OHI(2034-64)
500ppm	Russia (2014) EE (2014)	8% (2094) - 16% (2024) Exception: 100% (2014)	Configuration variable over time	Configuration variable over time	Russia (2044-74) EE (2044-64) OHI(2044-64)

From column A it can be seen that the emission constraints under KyEv are not binding for Russia, EE, Japan and EUR. For Russia and EE this is true over the entire time horizon. For Japan and EUR, the constraints are binding initially but cease to be binding in 2034 due to these regions' high rates of carbon saving technological progress in the BAU case. Under KyDyn, only Russia and EE face non-binding constraints (over the entire horizon), whereas in the 500ppm case the constraints are binding in all regions and all periods except for Russia and EE in 2014.[17]

The three abatement scenarios are thus characterized by different degrees of strictness which imply different potentials for trade in 'hot air'. This is confirmed by column (B) which tells us that under KyEv between 84 and 100 percent of abatement duties are satisfied by buying permits. In the stricter KyDyn case the corresponding range is 43 to 92 percent, whereas the importance of ET in the 500ppm case is much smaller still (3 to 16 percent).[18]

The configuration of buyers and sellers of permits (columns C and D) is the same under KyEv and KyDyn: The US and OHI are buyers over the entire time horizon, whereas Russia and EE are sellers. EUR and Japan initially are buyers but switch their role from 2024 on. The 500ppm scenario is different from these cases. It implies a variable buyer-seller configuration over time but, as mentioned above, the traded amounts are small. The variability of the buyer-seller configuration indicates that the initial allocation of permits in this scenario ("equal burden sharing") is already close to a least-cost allocation, so small perturbations may turn a buyer into a seller or vice versa.

Finally, column D tells us that in all scenarios only Russia, EE, and OHI will benefit from global warming - at least for some time - and will thus be hurt by lower global carbon levels. All other regions benefit from global carbon abatement.

[17] The somewhat outstanding results for the year 2014 occurbecause of the model's set-up to run in 10 year time steps and therefore 2014 being thefirst trading opportunity with respect to the first commitment period.
[18] An interesting feature of the KyEv case is that the trading potential slightly rises over time, since Japan and Europe dispose of increasing amounts of abundant permits which they start selling from 2024 on (see column D). In the KyDyn case with its increasingly stricter abatement requirements the trading potential decreases over time.

4.3 Effects of Trade Restrictions

As mentioned above, each abatement scenario is run with several degrees of constraints on emissions trading. We now present the effects of imposing abatement targets, combined with the constraints on the admissible degree of trading. All effects will be expressed as percentage changes relative to the BAU case.

We first address the effects on carbon efficiency, see Table 4. Since the effects turned out to be nearly continuous in the degree of admissible trade, we restrict the presentation to the cases of 100 percent (full trade) and 50 percent.

It is convenient to start the discussion with a comparison of the various abatement scenarios when trade is unrestricted. When we compare KyEv100 with KyDyn100, it is evident that from 2024 onwards the latter scenario implies substantially higher levels of carbon efficiency than the former in all of the Annex B regions. The reason is, of course, that the KyDyn case imposes stricter limits on emissions than KyEv. This effect is particularly pronounced in Japan and EUR, that is in the regions that are largely unconstrained under KyEv but face binding constraints under KyDyn. In Japan the level of energy efficiency in 2094 under KyDyn is almost twice the BAU level, whereas under KyEv it is only 6 percent above BAU.

It should be noted that in 2014 - in contrast to later periods - all the Annex B buyer countries have lower carbon efficiency under KyDyn than under KyEv. KyDyn thus implies an inter-temporal shift in R&D efforts: The value of decarbonization in the 'future' relative to that in the 'present' is higher under KyDyn than under KyEv, and R&D will be reallocated accordingly.

The situation is different in non-Annex B regions (HIO, MI, LMI, LI, China, India, Africa). Here, carbon efficiency under KyDyn is below that under KyEv in *all* periods. The reason is that these regions benefit - via reduced climate-related damage - from the more aggressive reduction in carbon emissions undertaken by the Annex B regions under KyDyn; as a result these regions need to undertake less carbon-saving R&D.[19] This is a form of carbon leakage, this time related to a disincentive with respect to R&D.

The 500ppm100 case is quite similar to the KyDyn100 case as far as the Annex B regions are concerned. With respect to the non-Annex B regions there is of course a huge difference, because they face abatement obligations in this scenario which they do not under KyDyn. As a result, their carbon efficiency is substantially higher now than under BAU (and under KyEv and KyDyn). The most pronounced efficiency improvement occurs in China, where the efficiency level in the second half of the century is about 24 percent above BAU.

We can now address the effects of restricting the trade in carbon rights. When emissions trading under KyEv is restricted to 50 percent, the buyer regions USA and OHI significantly raise their carbon efficiency whereas the sellers Russia and EE as well as EUR reduce it. The logic behind this result is evident: Buyers have to switch to domestic action to fulfill their abatement obligations and therefore raise carbon-saving R&D. On the other hand, sellers now are confronted with a smaller market. This scale effect reduces their incentive to undertake R&D. However, in addition to this basic logic, there are secondary effects related to the level of global emissions. Since KyEv100 entails significant amounts of 'hot air', KyEv50 implies a smaller global carbon budget. This implies that the overall demand for carbon abatement rises. As a result, the seller region Japan (which is a seller from 2024 onwards) has an additional incentive to engage in carbon-saving R&D toward the end of the century, such that carbon efficiency under KyEv50 rises relative to KyEv100.

In the non-Annex B regions KyEv50 goes along with lower carbon efficiency than KyEv100. This is again related to the lower level of global carbon emissions in the former scenario which implies that climate damage in non-Annex B regions is lower, both in terms of total as well as marginal damage. Since marginal avoided damage is the payoff from any dollar spent on carbon-saving R&D, the incentive to undertake these expenditures is reduced.

In the KyDyn scenario the effects of trade restrictions are qualitatively similar to those under KyEv but less pronounced. The reason for this is that under full ET the potential for trade is smaller than under KyEv and so is the effect of restricting trade. In the seller regions EE, Japan and EUR KyDyn50 implies a smaller level of carbon efficiency than KyEv100, but the difference is very small towards the end of the century. The situation is similar for Russia, but towards the end of the century we even see higher carbon efficiency in the case of restricted trade. The explanation for these dynamics is that in KyDyn the overall abatement

[19] Reduced damage also explains why R&D under KyEv100 is lower than under BAU in most non-Annex B

requirements become increasingly aggressive over time. Therefore, restrictions to trade do reduce the size of the market on which permits can be sold, but the permits that *can* be sold become more and more valuable, implying an increasing incentive for carbon saving R&D on the part of the sellers.

This logic is mirrored by the results for the buyer regions USA and OHI: While trade restrictions imply substantially higher carbon efficiency in the first half of the century, the effect becomes smaller in the second half. That is, as global carbon limits become stricter over time the sellers' comparative advantage gets accentuated when trade is restricted, and the buyers undertake less R&D.

In the non-Annex B countries the effects of trade restrictions are mixed in sign but small in size. This is intuitively plausible: Since trade restrictions have less effect on the global carbon level under KyDyn than under KyEv (less 'hot air'), full trade and restricted trade differ little in terms of climate damage and, consequently, in terms of induced decarbonization.

In the 500ppm case restrictions to emissions trading trigger very little deviations in terms of carbon efficiency from the case of unrestricted trade. The reason is that the trade volume is very small even in the unrestricted case since there is no 'hot air' and the profile of initial entitlements is already close to a least-cost allocation.

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regions in the second half of the century.

Table 4: Effects on Carbon Efficiency (average percentage change from BAU)

		KyEv100	KyEv50	KyDyn100	KyDyn50	500ppm100	500ppm50
Annex B							
EE	**2014**	0.59	-0.29	0.59	-0.43	0.58	-0.60
	2024-2054	1.23	0.06	11.37	4.46	13.02	13.02
	2064-2094	9.25	2.07	36.85	35.27	32.70	32.62
EUR	**2014**	0.33	1.79	0.03	1.79	-0.45	1.80
	2024-2054	1.24	-0.47	12.58	4.96	14.23	14.14
	2064-2094	0.32	0.05	35.38	32.82	31.39	31.55
Japan	**2014**	-0.12	3.63	-1.81	3.62	-1.81	3.62
	2024-2054	2.60	-0.84	24.52	9.40	28.29	28.56
	2064-2094	1.14	1.51	66.06	61.62	58.09	57.79
OHI	**2014**	-0.25	12.04	-0.41	12.09	-0.85	11.97
	2024-2054	1.35	11.97	11.47	17.60	12.83	11.95
	2064-2094	1.25	9.71	31.81	31.31	28.55	28.40
Russia	**2014**	2.29	1.26	2.29	1.13	2.31	0.42
	2024-2054	0.69	-0.26	10.74	4.08	12.17	12.23
	2064-2094	2.35	-1.28	31.72	37.33	28.35	36.18
USA	**2014**	-0.01	-0.14	-0.28	-0.29	-0.67	-0.73
	2024-2054	1.28	16.52	11.14	19.64	12.76	12.41
	2064-2094	0.80	17.94	28.81	30.23	25.92	25.99
Non-Annex B							
Africa	**2014**	0.00	-0.05	-0.18	-0.20	-0.53	-0.37
	2024-2054	-0.56	-0.62	-0.71	-0.76	5.06	5.70
	2064-2094	-0.44	-0.75	-0.63	-0.87	8.44	8.43
China	**2014**	0.01	-0.15	-0.21	-0.29	-0.77	-0.80
	2024-2054	-0.12	-0.27	-0.39	-0.47	10.39	10.47
	2064-2094	-0.13	-0.28	-0.56	-0.63	24.14	23.98
HIO	**2014**	0.13	0.06	-0.49	-0.03	-0.35	-0.12
	2024-2054	0.08	-0.25	0.01	-0.15	6.78	7.14
	2064-2094	1.00	-0.24	-0.37	0.79	12.26	10.58
India	**2014**	-0.07	-0.16	-0.25	-0.29	-0.62	-0.69
	2024-2054	0.12	0.03	-0.26	-0.11	7.66	7.74
	2064-2094	-0.15	-0.28	-0.28	-0.54	16.46	16.64
LI	**2014**	0.09	0.03	-0.06	-0.07	-0.29	-0.30
	2024-2054	0.18	0.04	-0.08	-0.12	6.80	6.97
	2064-2094	-0.35	-0.30	-0.41	-0.50	14.21	14.06
LMI	**2014**	-0.02	-0.26	-0.26	-0.22	-0.49	-0.66
	2024-2054	0.02	-0.10	-0.20	-0.27	8.61	8.77
	2064-2094	-0.03	-0.14	-0.43	-0.43	18.80	18.81
MI	**2014**	-0.20	-0.30	-0.27	-0.42	-0.87	-0.80
	2024-2054	0.04	-0.11	-0.26	-0.31	8.83	8.86
	2064-2094	-0.20	0.10	-1.07	-0.84	15.75	16.87

It remains to discuss the effects on consumption of our carbon abatement scenarios and of restrictions to emissions trading within these scenarios. These are presented in Table 5. On a world-wide scale we find that KyEv has practically no impact on consumption. This holds irrespective of the degree of emissions trading, which suggests that the economic costs of trade restrictions are just offset by the more pronounced reduction of climate damage when trade is restricted.

Table 5: Effects on Consumption (average percentage change from BAU)

		KyEv100	KyEv50	KyDyn100	KyDyn50	500ppm100	500ppm50
Annex B							
EE	**2014**	0.00	0.00	-0.01	0.01	-0.01	0.00
	2024-2054	-0.002	0.023	-0.151	-0.071	-0.201	-0.207
	2064-2094	-0.109	-0.027	-0.851	-0.772	-0.739	-0.805
EUR	**2014**	0.00	0.00	0.00	0.00	0.00	0.00
	2024-2054	0.000	0.005	-0.020	-0.008	-0.017	-0.015
	2064-2094	0.011	0.042	-0.039	-0.031	0.055	0.070
Japan	**2014**	0.00	0.00	-0.01	0.00	-0.01	-0.01
	2024-2054	-0.001	0.001	-0.032	-0.020	-0.031	-0.031
	2064-2094	0.007	0.013	-0.093	-0.089	-0.048	-0.053
OHI	**2014**	0.00	-0.02	0.00	-0.02	0.00	-0.03
	2024-2054	-0.003	-0.041	-0.042	-0.064	-0.047	-0.051
	2064-2094	-0.023	-0.062	-0.199	-0.205	-0.159	-0.156
Russia	**2014**	0.01	0.01	0.00	0.01	-0.01	0.02
	2024-2054	-0.011	0.006	-0.196	-0.087	-0.279	-0.288
	2064-2094	-0.077	0.020	-0.915	-0.882	-0.885	-0.793
USA	**2014**	0.00	0.00	0.00	0.00	0.00	0.00
	2024-2054	-0.005	-0.069	-0.058	-0.093	-0.052	-0.050
	2064-2094	-0.003	-0.111	-0.262	-0.281	-0.161	-0.159
Non-Annex B							
Africa	**2014**	0.01	0.00	0.01	0.00	0.03	0.04
	2024-2054	-0.002	0.006	0.004	0.009	-0.149	-0.139
	2064-2094	0.082	0.123	0.151	0.171	-0.745	-0.736
China	**2014**	0.00	0.00	0.01	0.01	0.02	0.03
	2024-2054	-0.003	-0.014	0.019	0.004	-0.407	-0.431
	2064-2094	-0.043	-0.044	0.035	0.022	-1.399	-1.470
HIO	**2014**	-0.01	0.00	-0.01	-0.01	0.03	0.03
	2024-2054	0.004	0.005	0.007	0.008	-0.081	-0.078
	2064-2094	0.018	0.017	0.037	0.048	-0.482	-0.507
India	**2014**	0.00	0.00	0.00	0.00	0.04	0.05
	2024-2054	0.004	0.002	0.012	0.013	-0.220	-0.236
	2064-2094	0.018	0.071	0.148	0.122	-1.032	-1.087
LI	**2014**	0.00	0.00	0.00	0.00	0.04	0.05
	2024-2054	0.021	0.029	0.026	0.032	-0.131	-0.136
	2064-2094	-0.019	0.009	0.042	0.041	-0.820	-0.805
LMI	**2014**	0.00	0.00	0.00	0.00	0.02	0.01
	2024-2054	0.000	0.002	0.006	0.008	-0.125	-0.125
	2064-2094	0.006	0.036	0.054	0.056	-0.485	-0.491
MI	**2014**	0.00	0.00	0.00	0.00	0.01	0.01
	2024-2054	0.001	0.004	0.003	0.005	-0.049	-0.041
	2064-2094	0.004	0.022	0.040	0.037	-0.251	-0.206
World	***2014***	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
	2024-2054	*0.000*	*-0.014*	*-0.025*	*-0.026*	*-0.096*	*-0.097*
	2064-2094	*-0.004*	*-0.005*	*-0.082*	*-0.080*	*-0.441*	*-0.444*

In the KyDyn and 500ppm scenarios we find reductions of global consumption by up to 0.08 and 0.44 percent, respectively. It is interesting to note that even in these cases the degree of admissible emissions trading has virtually no influence on global consumption. This may appear surprising since in these scenarios the global carbon trajectories differ less between the full ET and the restricted ET cases than under KyEv (less 'hot air'). This would then suggest that there is less scope for reduced climate damage to offset the 'excess costs' imposed by trade restrictions. But, on the other hand, there is also less potential for emissions trading in these scenarios than in the KyEv scenario, so restrictions to trade are less detrimental in terms of 'excess costs'.

On a regional scale, effects on consumption do in some regions - but not all - depend on the admissible degree of ET. Under KyEv the permit seller regions Russia, EE, EUR, and Japan tend to benefit somewhat from trade restrictions while the permit buyers USA and OHI incur a loss. Thus, the enhanced decarbonization in permit buyer regions tends to be a poor substitute for the possibility to purchase carbon abatement from abroad. As concerns the non-Annex B regions, most of them benefit from trade restrictions, due to reduced climate damage. Under KyDyn, trade restrictions have little impact on regional consumption. The same holds for the 500ppm scenario.

5. Conclusions

This paper has examined the implications of restricting the tradability of carbon rights in the presence of induced technological change. Unlike earlier approaches aiming at exploring the tradability-technology linkage we have focused on climate-relevant 'carbon-saving' technological change. The following conclusions have emerged.

- Restricting the trade in carbon rights triggers additional investments in carbon saving technological progress in those regions that are buyers of carbon rights, while depressing these investments in seller regions.
- In scenarios involving 'hot air' regions that are not committed to carbon abatement will reduce their investment in carbon saving technological progress in response to trade restrictions due to the implied reduction in carbon damage. Feedback from the climate system is thus crucial for analyzing the effects of trade restrictions.
- The effect of trade restrictions on carbon saving technological progress depends on the scope for carbon trade inherent in each particular carbon abatement scenario. Scenarios involving 'hot air' entail comparatively stronger effects of trade restrictions on carbon saving technological progress. Likewise, scenarios in which the initial allocation of carbon rights differs much from the least-cost allocation also entail a stronger effect.
- If global carbon restrictions become stricter over time, the incentives for sellers of carbon rights to undertake carbon saving investments may rise as emissions trading gets restricted, the reason being that permits to be sold become more valuable as abatement requirements are tightened.

- In terms of consumption, restrictions to emissions trading have only small effects. Qualitatively, buyers of carbon permits tend to be negatively affected by trade restrictions. Sellers of carbon permits benefit from trade restrictions. Regions that are not committed to carbon abatement may benefit from trade restrictions to the extent that global carbon levels and the ensuing climate damage get reduced.

Overall, it may be concluded that the debate on whether or not to restrict the trade in carbon permits in the presence of induced carbon saving technological progress is difficult to settle on efficiency grounds. Trade restrictions mainly induce a reallocation of R&D efforts among buyers and sellers and a small shift of welfare from the former to the latter, but the worldwide welfare effects are almost invisible. Thus, the issue seems to be largely of a distributional or political nature with little implications for global welfare.

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Appendix 1: Description of RICE / DICE models

The RICE (**R**egional **I**ntegrated model of **C**limate and the **E**conomy) model family analyzes the interactions between climate and the economy. Being growth models as well as integrated assessment models, they analyze the welfare effects of climate policy in the framework of intertemporal utility maximization. The first aggregated version (DICE, **D**ynamic **I**ntegrated model of **C**limate and the **E**conomy) was described in Nordhaus (1994) and later followed by the regionalized version of Nordhaus and Young (1996). A major revision of the models that encompasses updates of data as well as methodological changes has been made at the end of the nineties by Nordhaus and Boyer (2000). These updated models are known as RICE/DICE-99 and are available at www.econ.yale.edu/~nordhaus/homepage/homepage.htm in the form of GAMS and Excel files.

RICE is a growth model. According to neoclassical growth theory of the Ramsey-type, a representative agent maximizes intertemporal utility. The decision either to consume or to invest determines the development of the capital stock. This, in turn, determines consumption possibilities in later periods. Therefore, there is a trade-off between lower consumption (and higher investment) today and higher consumption possibilities in the future. Furthermore, the world in RICE-99 is divided into 13 (world-) regions that can be grouped into trading blocs for ET.

RICE is also an integrated assessment model that takes into account the (mostly negative) feedbacks of carbon emissions on the economy. Anthropogenic emissions that result from production feed into a climate module of the model. In the climate module, rising carbon concentrations lead to rising temperatures that result in different feedbacks on the outputs of the different regions. Since the (time-lagged) feedbacks on production are mostly negative, there is a second trade-off between consumption possibilities today and tomorrow. Lower production today means lower associated emissions. These cause lower negative feedbacks and therefore higher production possibilities in later periods. Anthropogenic GHG emissions become an additional factor that enters intertemporal utility maximization.

Appendix 2: Derivation of Energy Capital R&D-Stocks

Table - A 1 shows R&D energy capital stocks for the world regions of RICE-99. The procedure is as follows: From an IEA-database[20] (IEA (1997, showing annual governmental R&D budgets on energy capital from 1974 – 2000), all annual fossil fuel related R&D budgets have been aggregated until 1994. These aggregated, annual government R&D budgets have been scaled up using figures on the percentage of government shares on gross domestic R&D expenditures (OECD (1987 - 1998). Missing data has been interpolated. According to the perpetual inventory model in equation (7), these yearly investments build up the capital stock using a depreciation rate of 5%. Due to the long period of twenty years, no initial capital stock is applied. The resulting national capital stocks for 1994 (the benchmark year) are aggregated according to the world regions in RICE-99. However, these data are only available for OECD countries, that is, they apply only to the RICE-99 regions Japan, OECD Europe, OHI and USA. For the remaining regions, the R&D energy capital stocks are inferred by the method proposed by Buonanno et al. (2001): the ratio of the R&D capital stocks and physical capital stocks of these four regions is used to infer the missing R&D energy capital stocks for the other regions.

Table - A 1: R&D Stocks of Energy Knowledge

World Regions	R&D Energy Capital Stock 1994 (bill 1990 US$)
Annex B	
EE (Eastern Europe)	1,288
EUR (OECD Europe)	11,076
Japan	25,986
OHI (Other High Income Countries)	3,415
Russia	1,089
USA	22,574
Non-Annex B	
Africa	0,485
China	1,792
HIO (High Income OPEC)	1,298
India	0,975
LI (Low Income Countries)	1,500
LMI (Lower & Middle Income Countries)	3,561
Middle Income Countries (MI)	4,239
Source: IEA 1997; own calculations	

[20] See also: www.iea.org/stats/files/rd.htm